Investigation of the ITS-90 Subrange Inconsistencies for 25.5 Ω SPRTs

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ABSTRACT

The International Temperature Scale of 1990 provides greater flexibility than the International Practical Temperature Scale of 1968, Amended Edition 1975, through the use of more fixed points and more temperature subranges. The present investigation examined the ranges of 83.8058 K to 273.16 K and 273.15 K to 933.473 K for 25.5 Ω standard platinum resistance thermometers. These two ranges have multiple subranges that partly overlap, creating inconsistencies. The magnitude of the inconsistencies in the interpolation between the appropriate defining fixed points in the temperature overlap regions were investigated. The results show that in all 16 possible combinations of subranges, there were no significant differences between manufacturer/models and that the inconsistencies in most cases are within estimated measurement uncertainties.

SUBJECT INDEX: International Temperature Scale of 1990 (ITS-90), Platinum resistance thermometers and Thermometry, Fixed Points

INTRODUCTION

Adoption of the International Temperature Scale of 1990 (ITS-90) (1) has provided an increase in the number of temperature subranges available for calibration of standard platinum resistance thermometers (SPRTs) over that provided by the International Practical Temperature Scale of 1968, Amended Edition of 1975 (IPTS-68(75)) (2). The long-stem 25.5 Ω SPRT may be calibrated over the full range of 83.8058 K (argon triple point) to 933.473 K (aluminum freezing point) or 692.677 K (zinc freezing point) for those thermometers that contain mica (3). Within these ranges, all possible temperature subranges may be realized by measuring an SPRT at the ITS-90 defining fixed points that lie within the corresponding temperature limits. By calibrating an SPRT at these fixed points, an investigation may be performed of the inconsistencies at overlapping subranges that arise from the use of different fixed points and different deviation functions for the interpolation of temperature between those defining fixed points. For a given $W(T_{90})$ [$W(T_{90})=R(T_{90})/R(273.16\ K)$], these interpolations, which are slightly different for each subrange, will result in different indicated temperatures of an SPRT.

The staff of the Platinum Resistance Thermometry (PRT) laboratory at the National Institute of Standards and Technology (NIST) has been investigating these subrange inconsistencies for 25.5 Ω SPRTs. This has been accomplished by calibrating the SPRTs at all of the ITS-90 defining fixed points from the argon triple point to the freezing point of zinc or aluminum, depending on the particular SPRT. The temperature inconsistencies in the overlap regions of the subranges are inherent in the ITS-90 due to the scale mathematics and variations in the construction of the SPRTs. The mathematical functions and scale criteria for the construction of an SPRT were designed to minimize the subrange inconsistencies. The addition of multiple subranges has increased the flexibility in the use of an SPRT as a defining standard of the ITS-90. However, this increased flexibility has created an uncertainty as to which temperature subrange should be used for the calibration of that SPRT. All of the ITS-90 temperature subranges are considered to be of equal status, with no subrange being more accurate than another. This study of the overlapping temperature regions of the subranges was an attempt to determine the approximate size of the inconsistencies and whether there are any systematic differences between subranges. Also, the study investigated the existence of any systematic differences between manufacturer/models of SPRTs.

EXPERIMENTAL DETAILS

NIST maintains all of the defining fixed points of the ITS-90 over the range of 83.8058 K to 1234.93 K (silver freezing point). Using these fixed points, the staff of the PRT laboratory calibrates long-stem 25.5 Ω SPRTs as the ITS-90 defining interpolation device from the argon triple point to either the zinc or aluminum freezing point. Only SPRTs constructed either with silica-glass supports and silica-glass sheaths or ceramic supports with Inconel sheaths may be used over the temperature subrange from 273.15 K to 933.473 K. Those SPRTs with mica supports for their platinum windings or with borosilicate glass sheaths should be used only to the freezing point of zinc. Table I summarizes the following information: 1) the 16 possible temperature overlap regions based on the seven different temperature subranges; 2) the fixed points required for each of those seven subranges; and 3) the six baseline subranges.

For practicality, each subrange is designated by the hottest or coldest fixed point with an unique subscript that is used by NIST to also identify its deviation function (4). Using this subscript for identification, the seven temperature subranges used in this study are as follows: 273.15 K to 933.473 K is Al_7, to 692.677 K is Zn_8, to 505.078 K is Sn_9, to 429.7485 K is In_{10}, to 302.9146 K is Ga_{11}, 302.9146 K to 234.3156 K is Hg_5 and 273.16 K to 83.8058 K is Ar_4.

Table I: Temperature overlap regions based on the combinations of the seven subranges used to study subrange inconsistencies (subrange - baseline subrange). Each subrange is designated by the hottest or coldest fixed point and a unique subscript used to define its deviation function.

Subrange Combination	Fixed Points Required for Each Subrange Combination	Temperature Overlap Region, K
Zn_8 - Al_7	(Zn, Sn, TPW) - (Al, Zn, Sn, TPW)	273.15 to 692.677
Sn_9 - Al_7	(Sn, In, TPW) - (Al, Zn, Sn, TPW)	273.15 to 505.078
In_{10} - Al_7	(In, TPW) - (Al, Zn, Sn, TPW)	273.15 to 429.7485
Ga_{11} - Al_7	(Ga, TPW) - (Al, Zn, Sn, TPW)	273.15 to 302.9146
Hg_5 - Al_7	(Hg, Ga, TPW) - (Al, Zn, Sn, TPW)	273.15 to 302.9146
Sn_9 - Zn_8	(Sn, In, TPW) - (Zn, Sn, TPW)	273.15 to 505.078
In_{10} - Zn_8	(In, TPW) - (Zn, Sn, TPW)	273.15 to 429.7485
Ga_{11} - Zn_8	(Ga, TPW) - (Zn, Sn, TPW)	273.15 to 302.9146
Hg_5 - Zn_8	(Hg, Ga, TPW) - (Zn, Sn, TPW)	273.15 to 302.9146
In_{10} - Sn_9	(In, TPW) - (Sn, In, TPW)	273.15 to 429.7485
Ga_{11} - Sn_9	(Ga, TPW) - (Sn, In, TPW)	273.15 to 302.9146
Hg_5 - Sn_9	(Hg, Ga, TPW) - (Sn, In, TPW)	273.15 to 302.9146
Ga_{11} - In_{10}	(Ga, TPW) - (In, TPW)	273.15 to 302.9146
Hg_5 - In_{10}	(Hg, Ga, TPW) - (In, TPW)	273.15 to 302.9146
Hg_5 - Ga_{11}	(Hg, Ga, TPW) - (Ga, TPW)	273.15 to 302.9146
Hg_5 - Ar_4	(Hg, Ga, TPW) - (Ar, Hg, TPW)	234.3156 to 273.16

As shown in Table II, 50 randomnly selected SPRTs were calibrated at all possible ITS-90 defining fixed points over the range from 83.8058 K or 234.3156 K to 692.677 K or 933.473 K. The SPRTs represent three thermometer manufacturers* and six different manufacturer/models. They were used to investigate whether different models yield systematically different results.

Table II: List of manufacturers, models and number of each type used for each temperature subrange.

Manufacturer/Model*	Temperature subranges and number of SPRTs						
	Al_7	Zn_8	Sn_9	In_{10}	Ga_{11}	Hg_5	Ar_4
L&N 8163	2	17	17	17	17	17	15
L&N 8167	0	6	6	6	6	6	3
Rosemount 162C	0	4	4	4	4	4	3
Rosemount 162CE	11	12	12	12	12	12	10
YSI 8163	0	5	5	5	5	5	5
YSI 8167	0	6	6	6	6	6	6
Total Number	13	50	50	50	50	50	42

The calibration of the SPRTs on the ITS-90 followed standard NIST procedures (5). First, the thermometers were annealed, with special handling given to those SPRTs requiring calibration at the aluminum freezing point. Second, the thermometers were measured at the triple point of water (TPW) (273.16 K) to establish a baseline for their stability during the calibration. Third, the thermometers were sequentially measured at the fixed points, decreasing in hotness, and bracketed by TPW measurements. An example of the measurement sequence used to calibrate an SPRT is: anneal, TPW, Al, TPW, Zn, TPW, Cd, TPW, Sn, TPW, In, TPW, Ga, TPW, Hg, TPW, Ar and TPW. The measurements were performed using a semi-automated, computer-controlled data acquisition system. A commercially available 30 Hz resistance bridge, thermostatically controlled ac/dc reference resistors, a digital multimeter, thermometer port connections and scanners were all connected via an IEEE-488 bus. The data acquisition system allows the computer to accept measurement data only when the thermometer is in thermal equilibrium. All results reported here are corrected to zero-power dissipation to nullify the error that occurs from self-heating effects. Zero-power values were calculated by making measurements at 1 mA and 2 mA, and extrapolating to 0 mA.

To determine the subrange inconsistencies for each SPRT, the coefficients for the appropriate deviation function were calculated for each temperature subrange. These deviation functions were then used to compare the temperature differences of the subranges in the overlapping regions.

RESULTS

Descriptive and inferential statistical techniques were used to analyze the subrange inconsistency data. Inferentially, a single factor (manufacturer/model) analysis of variance (ANOVA) was conducted for each overlap region to determine whether there were any statistically significant differences between manufacturer/models. ANOVA is a procedure for comparing multiple populations and makes only one comparison to determine whether any of the populations differ from the rest. In the case of a significant ANOVA, post-hoc comparison tests (e.g. Scheffé) evaluating individual population means are performed to determine the actual source of differences (6). The results of the 16 ANOVAs showed no significant differences between the manufacturer/models.

Descriptively, the following univariate statistics were determined: mean, maximum, upper fourth (Q3), median, lower fourth (Q1), minimum, range, and interquartile range (fourth spread or Q3-Q1). The interquartile range represents the difference between the upper fourth (75% or Q3) cutoff point and the lower fourth (25% or Q1) cutoff point within which 50% of the subrange inconsistency values lie for a given subrange. The range is of very limited value as a measure of dispersion. The interquartile range, however, is a more sensitive indicator of dispersion, providing a more useful description of the variability in the distribution of the subrange inconsistencies. Specifically, it is a reflection of the amount of dispersion in a given overlap region (7). These statistics are shown in Table III. Additionally, examples of the subrange inconsistencies in the temperature overlap regions are shown in Figures 1 through 7. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 and Q1 and the thick solid line represents the median of the curves.

Table III: Results for the subrange inconsistencies in the 16 temperature overlap regions.

Subrange Combination	max mK	Q3 mK	median mK	Q1 mK	min mK
Zn_8 - Al_7	0.40	0.22	0.06	-0.10	-0.27
Sn_9 - Al_7	0.28	0.24	0.14	-0.06	-0.24
In_{10} - Al_7	0.37	-0.20	-0.35	-0.44	-0.52
Ga_{11} - Al_7	0.11	-0.04	-0.09	-0.22	-0.27
Hg_5 - Al_7	0.21	0.06	-0.21	-0.30	-0.41
Sn_9 - Zn_8	0.41	-0.16	-0.31	-0.38	-0.44
In_{10} - Zn_8	0.39	-0.24	-0.28	-0.37	-0.45
Ga_{11} - Zn_8	0.23	-0.06	-0.16	-0.20	-0.24
Hg_5 - Zn_8	0.28	0.05	-0.20	-0.28	-0.38
In_{10} - Sn_9	0.40	0.19	0.08	-0.21	-0.42
Ga_{11} - Sn_9	0.30	0.22	0.10	-0.15	-0.28
Hg_5 - Sn_9	0.34	0.28	0.17	-0.17	-0.30
Ga_{11} - In_{10}	0.33	0.23	0.13	-0.04	-0.34
Hg_5 - In_{10}	0.37	0.25	0.18	0.09	-0.26
Hg_5 - Ga_{11}	0.18	0.11	0.09	0.08	-0.08
Hg_5 - Ar_4	0.27	0.20	0.17	0.10	-0.09

There are five subranges relative to the baseline subrange Al_7 that have overlapping temperature regions. Figure 1 depicts the results for the subrange inconsistencies in the temperature overlap region of Zn_8-Al_7. The maximum deviation is 0.40 mK, the range of the curves is 0.67 mK and Q3-Q1 is 0.32 mK. All of the curves must pass through zero at 505.078 K, since the freezing point of tin is a defining point for both of the subranges. The subrange inconsistencies, as shown in Table III, for the overlap regions of Sn_9-Al_7 and Hg_5-Al_7 have ranges and fourth spreads of inconsistencies similar to that of Zn_8-Al_7.

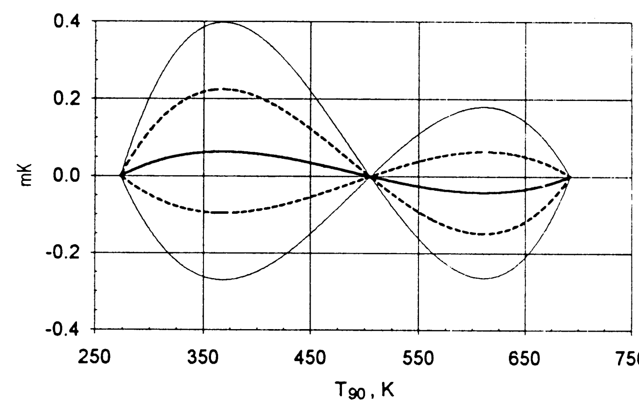

Figure 1. The curves depict the subrange inconsistencies for the subrange 273.15 K to 692.677 K (Zn_8) relative to the baseline subrange 273.15 K to 933.473 K (Al_7) for 13 SPRTs. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 (upper fourth) and Q1 (lower fourth) and the thick solid line represents the median of the SPRTs.

Figure 2 shows the overlap region of In_{10}-Al_7, which has the largest range of subrange inconsistencies. Analysis of the inconsistencies in this overlap region shows that the maximum deviation is -0.52 mK, the range is 0.89 mK and Q3-Q1 is 0.24 mK. The subrange combination, as shown in Table III, of Ga_{11}-Al_7 has the smallest range and interquartile range of subrange inconsistencies for those overlap regions relative to Al_7.

There are four subranges relative to the baseline subrange Zn_8 that have overlapping temperature regions. The largest range of subrange inconsistencies for these is for the temperature overlap region of Sn_9-Zn_8, and Figure 3 shows those inconsistencies. The maximum deviation is -0.44 mK, the range of the curves is 0.85 mK and Q3-Q1 is 0.22 mK. The subrange inconsistencies for the overlap region of In_{10}-Zn_8 has a similar range but a smaller fourth spread than that of Sn_9-Zn_8.

Figure 4 depicts the results for the subrange inconsistencies in the temperature overlap region of Ga_{10}-Zn_8. The maximum deviation is

-0.24 mK, the range of the curves is 0.47 mK and Q3-Q1 is 0.14 mK. Analysis of the subrange inconsistencies in the overlap region of Hg_5-Zn_8 shows that the maximum deviation is -0.38 mK, the range is 0.66 mK and Q3-Q1 is 0.33 mK.

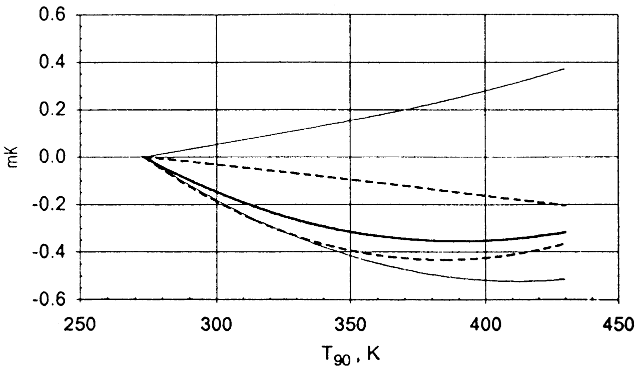

Figure 2. The curves depict the subrange inconsistencies for the subrange 273.15 K to 429.7485 K (In_{10}) relative to the baseline subrange 273.15 K to 933.473 K (Al_7) for 13 SPRTs. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 (upper fourth) and Q1 (lower fourth) and the thick solid line represents the median of the SPRTs.

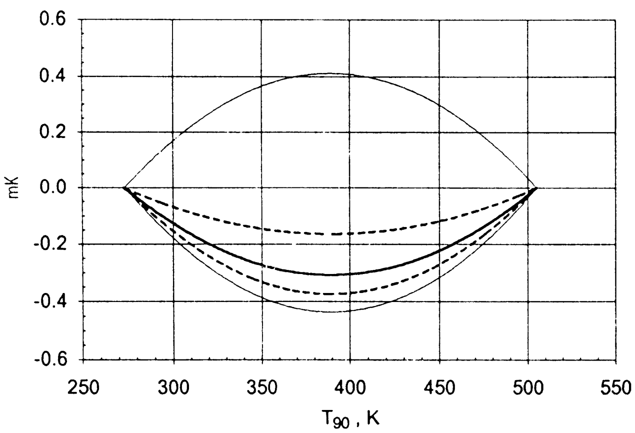

Figure 3. The curves depict the subrange inconsistencies for the subrange 273.15 K to 505.078 K (Sn_9) relative to the baseline subrange 273.15 K to 692.677 K (Zn_8) for 50 SPRTs. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 (upper fourth) and Q1 (lower fourth) and the thick solid line represents the median of the SPRTs.

There are three subranges relative to the baseline subrange Sn_9 that have overlapping temperature regions. The largest range of subrange inconsistencies is for the temperature overlap region of In_{10}-Sn_9, and Figure 5 shows those inconsistencies. The maximum deviation is -0.41 mK, the range of the curves is 0.82 mK and Q3-Q1 is 0.40 mK. The Ga_{11}-Sn_9 and Hg_5-Sn_9 overlap regions have similar ranges and fourth spreads for their subrange inconsistencies. The overlap region Ga_{11}-Sn_9 has a maximum deviation of 0.30 mK, a range of 0.58 mK and a Q3-Q1 of 0.37 mK. The overlap region Hg_5-Sn_9 has a maximum deviation of 0.34 mK, a range of 0.64 mK and a Q3-Q1 of 0.45 mK.

There are two subranges relative to the baseline subrange In_{10} that have overlapping temperature regions. Figure 6 depicts the results for the subrange inconsistencies in the temperature overlap region of Ga_{11}-In_{10}. The maximum deviation is -0.34 mK, the range of the curves is 0.67 mK and Q3-Q1 is 0.27 mK. The subrange inconsistencies for the overlap region of Hg_5-In_{10} have a maximum deviation of 0.37 mK, a range of 0.63 mK and a fourth spread of 0.16 mK.

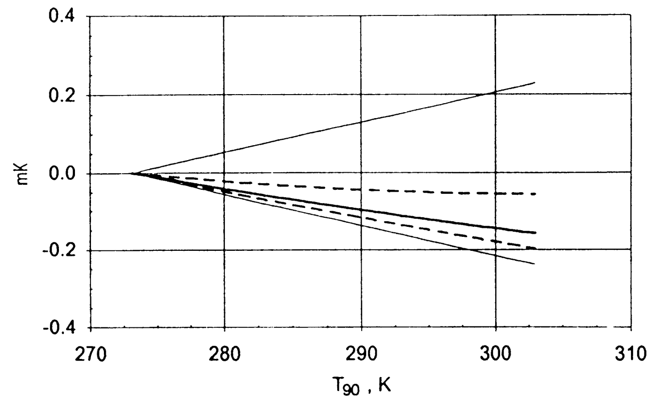

Figure 4. The curves depict the subrange inconsistencies for the subrange 273.15 K to 302.9146 K (Ga_{11}) relative to the baseline subrange 273.15 K to 692.677 K (Zn_8) for 50 SPRTs. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 (upper fourth) and Q1 (lower fourth) and the thick solid line represents the median of the SPRTs.

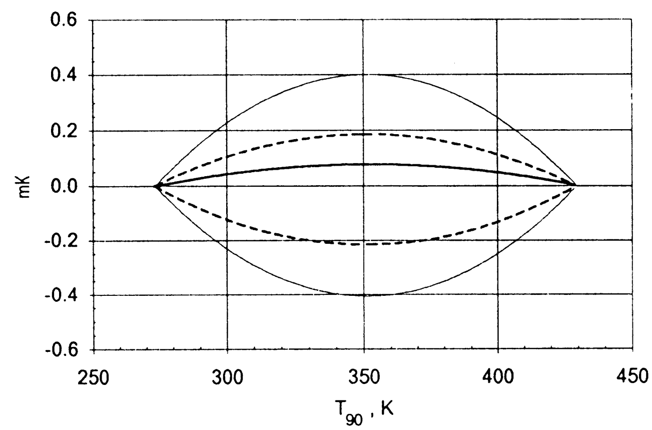

Figure 5. The curves depict the subrange inconsistencies for the subrange 273.15 K to 429.7458 K (In_{10}) relative to the baseline subrange 273.15 K to 505.078 K (Sn_9) for 50 SPRTs. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 (upper fourth) and Q1 (lower fourth) and the thick solid line represents the median of the SPRTs.

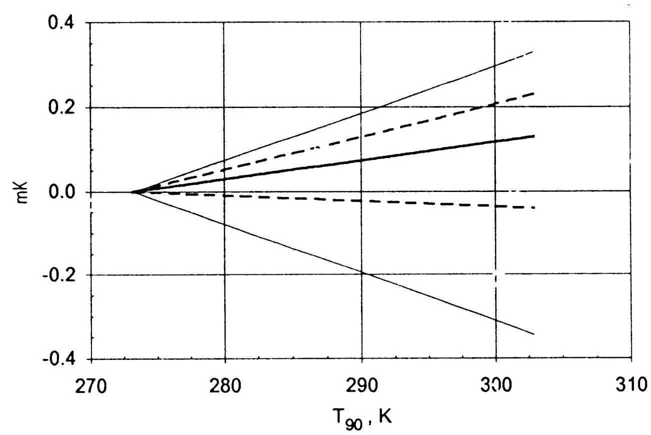

Figure 6. The curves show the subrange inconsistencies for the subrange 273.15 K to 302.9146 K (Ga_{11}) relative to the baseline subrange 273.15 K to 429.7485 K (In_{10}) for 50 SPRTs. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 (upper fourth) and Q1 (lower fourth) and the thick solid line represents the median of the SPRTs.

There is one subrange relative to the baseline subrange Ga_{11}, that has an overlapping temperature region. Additionally, there is one subrange relative to the baseline subrange Ar_4 that has an overlapping temperature region. Figure 7 depicts the results for the subrange inconsistencies in the temperature overlap regions of Hg_5-Ga_{11} and Hg_5-Ar_4. The subrange inconsistencies for the overlap region of Hg_5-Ga_{11} has a maximum deviation of 0.18 mK, a range of 0.26 mK and a fourth spread of 0.03 mK. The subrange inconsistencies for the overlap region of Hg_5-Ar_4 has a maximum deviation of 0.27 mK, a range of 0.36 mK and a fourth spread of 0.10 mK.

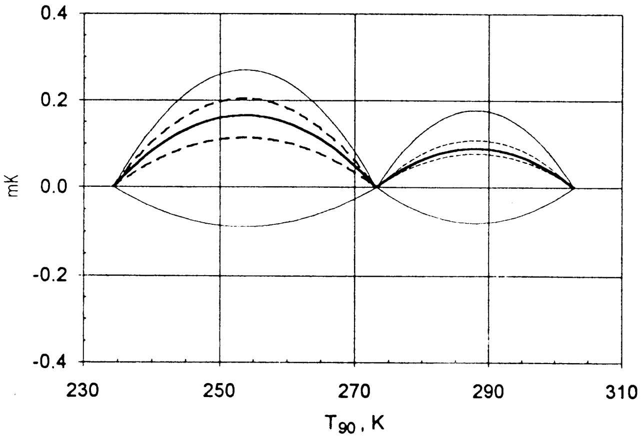

Figure 7. The curves show the subrange inconsistencies for the subrange 302.9146 K to 234.3156 K (Hg_5) relative to the baseline subrange 273.15 K to 302.9146 K (Ga_{11}) for 50 SPRTS and the subrange 302.9146 K to 234.3156 K (Hg_5) relative to the baseline subrange 83.8058 K to 273.16 K (Ar_4) for 42 SPRTs. The solid lines represent the maximum and minimum deviations from the baseline. The dashed lines represent Q3 (upper fourth) and Q1 (lower fourth) and the thick solid line represents the median of the SPRTs.

Analysis of the temperature overlap regions of either Sn_9 or In_{10} relative to either Zn_8 or Al_7 shows that their subrange inconsistencies are skewed in a negative direction. Adjustment of the realized temperature value of the In freezing point by about -0.25 mK makes those inconsistencies symmetrical. This suggests that the realized value of the NIST In freezing point may be high or the ITS-90 assigned value may be low.

CONCLUSIONS

The subrange inconsistencies, inherent in the realization of the ITS-90, for this set of 25.5 Ω SPRTs did not show any significant differences between manufacturer/models. The addition of multiple subranges to the ITS-90 has both increased the flexibility and the complexity in the use of an SPRT. Subrange inconsistencies arising from the overlap for the 16 temperature overlap regions are in most cases acceptable and are within the uncertainty of measurements, not considering the contributions from the subrange inconsistencies themselves. The magnitudes of the inconsistencies in the temperature overlap regions of In_{10}-Al_7 and Hg_5-Ar_4 are somewhat larger than desired. For most applications, however, even these inconsistencies are negligible. The interquartile range, reported for each temperature overlap region, showed that 50% of the subrange inconsistency data had a dispersion that was well within the remaining uncertainties of measurements. The data indicate that the ITS-90 mathematical functions and the assigned temperatures for the defining fixed points acceptably minimize the subrange inconsistencies in the temperature overlap regions.

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REFERENCES

* Disclaimer: Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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